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A Calibrated, Omnidirectional, LF Loop Antenna for GWEN

By

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This paper presents the design and performance characterization of a calibrated, omnidirectional, mobile LF receive antenna. This antenna is unique in its use of active circuitry to isolate two crossed-loop antenna elements from the combining network. A prototype was built for the Ground Wave Emergency Network (GWEN) in the 150 to 175 kHz band. The prototype has an effective height of 39 millimeters and is essentially omnidirectional over the GWEN frequency range.

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The antenna described here could not have been built without the knowledge and experience of Dr. Roswell Barnes (D-95) who designed all the active components needed for this project.

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INTRODUCTION

1.1 BACKGROUND

Noise in the Ground Wave Emergency Network (GWEN) band is dominated not by receiver noise but by external noise, namely atmospheric electrical storm activity (sferics). The effect of atmospheric noise on GWEN message transmissions has been of concern to MITRE for some time. An atmospheric noise study in the low frequency (LF) band is under way to obtain noise data and to characterize the electrical storm activity in this band. This characterization could be used in making future design modifications to the receiver filters in order to improve GWEN message reception if necessary.

A calibrated antenna is required to quantify the field strength of the recorded noise data. It should be as sensitive as the operational GWEN receiver antenna in present use. It should be portable, insensitive to local ground conditions, and should stay omnidirectional over the GWEN 25 kHz band. The present GWEN receiving antenna must be able to receive a 1.25 kHz bandwidth signal having a field strength as low as 40 dB µV/m with an acceptable signal to noise ratio. This minimum field strength figure is required by the LF receiver to properly process GWEN messages. The present GWEN LF receive antenna is a crossed-loop antenna with an effective height of -36 dB relative to a meter, and is designed to be omnidirectional in azimuth.

These criteria were used to build an antenna similar to the GWEN antenna which would be portable and have enough dynamic range to be used in the atmospheric noise study. The antenna built, however, is not restricted to the GWEN band (150-175 kHz), but can be modified to operate through the medium frequency (MF) band.

1.2 THEORY OF OPERATION

Phasing elements are required in the combining network of a crossed-loop antenna to keep the resulting pattern omnidirectional. The far-field azimuthal dependence of the magnetic field emanating from a loop whose plane is vertical (see figure 1a), and which is excited by a harmonic current, is

$$H_{\phi} = \frac{InA}{4\pi r^2} \cos(\phi) e^{i\omega t} \qquad (1)$$

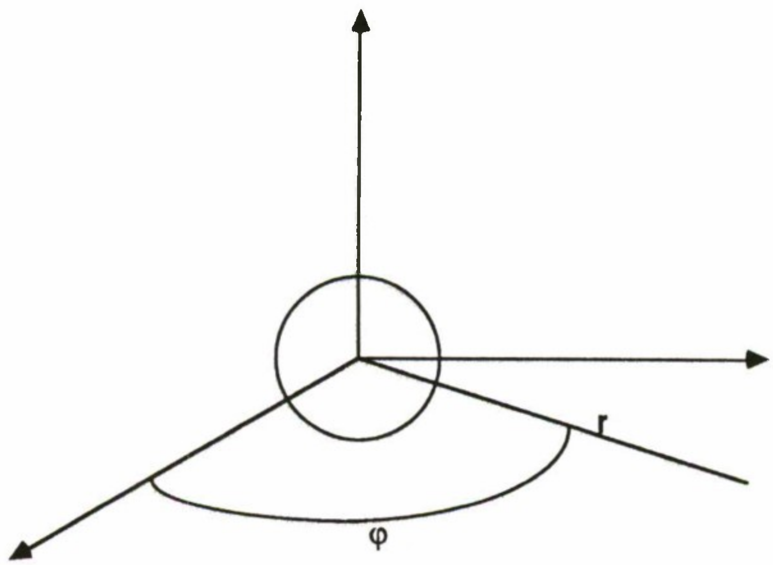

Figure 1a. Geometry of a Vertical Loop Antenna

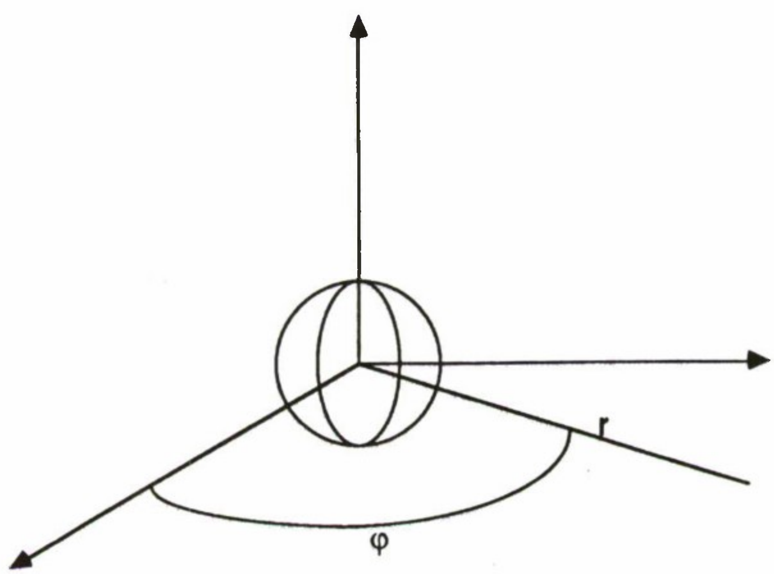

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Figure 1b. Geometry of a Vertical Crossed-Loop Antenna where

I = current amplitude in the loop
n = number of turns in the loop
A = area of the loop

When another vertical loop is placed at a right angle to the first one (see figure 1b), the resulting field will have the same azimuthal dependence with a 90 degree angle offset in azimuth. When combined, the magnetic field dependence of the vertical cross-loops will be

$$H_\phi = \frac{InA}{2\pi r^2}\left[\cos(\phi) + \cos(\phi + \pi/2)\right] e^{i\omega t}$$

$$= \frac{InA}{2\pi r^2}\left[\cos(\phi) + \sin(\phi)\right] e^{i\omega t} \quad . \tag{2}$$

When the input signals to the two loops of the antenna are put into quadrature (90 degrees out of phase), the resulting far-field expression for the cross-loops becomes

$$H_\phi = \frac{InA}{2\pi r^2}\left[\cos(\phi)\, e^{i(\omega t+\pi/2)} + \sin(\phi) e^{i\omega t}\right] \tag{3}$$

which reduces to

$$H_\phi = \frac{InA}{2\pi r^2}\left[\ \sin(\phi - \omega t) + i \cos(\phi - \omega t)\ \right] . \tag{4}$$

Since this antenna is constructed to be calibrated in field intensity, the magnitude of the fields must be measured. By definition, the magnitude of a complex quantity X is obtained by

$$X = \sqrt{(Re)^2 + (Im)^2}$$

where (Re) is the real part of X and (Im) its imaginary part.

The magnitude of the field component formulated in equation 4 reduces to

$$\left|H_\phi\right| = \frac{InA}{2\pi r^2} \quad . \tag{5}$$

It can be seen from equation 5 that the magnitude of this magnetic field component is independent of azimuthal angle.

Assuming electromagnetic reciprocity, it can be shown that a receive crossed-loop antenna with loop outputs in quadrature will have an omnidirectional sensitivity in azimuth.

SECTION 2

ANTENNA DESIGN AND CONSTRUCTION

2.1 ACTIVE VERSUS PASSIVE ANTENNA

Tests of the initial prototype indicated that the phasing components needed to put the two loops in quadrature affected the reactive nature of the loops. The phase component of one loop signal, relative to the other, changed enough over the GWEN band to seriously degrade the omnidirectional quality of the antenna that was sought. Eccentricity of the azimuthal radiation pattern at any given frequency within the band of interest is undesirable, as it will increase the error margin of the measured effective height of the antenna.

The antenna was then redesigned to isolate the receiving loops from the phasing components by using active electronic amplifiers. These active components are used to amplify the incoming signal, to isolate the loops of the antenna from the phasing components, and to merge the signals of the two loops. The use of electronic components may produce a host of problems particular to active systems. Some of these concerns are outlined below.

The amount of amplification given to the signal at the base of the antenna is limited by the leakage of amplified signal back to the input of the amplifiers. Too much amplification will allow the antenna to detect its own output signal. This leads to a positive (and therefore unstable) feedback mechanism. This positive feedback is an unstable control mechanism which leads to an oscillatory clipping in the output signal of the amplifier.

Another factor to be considered is the dynamic range offered by the antenna. This problem is of particular concern here, since this antenna is to be used in the study of impulsive electric storm activity. Some preliminary measurements have shown lightning "spikes" which are estimated to be greater than 95 dB above receiver noise levels. Characterizing electric storm activity demands a large dynamic range in the amplifiers. Clipping of the larger noise bursts is undesirable as it will eventually affect the amplitude characterization of LF noise data.

The bandwidth of the amplifiers and the rise time of the active circuits must also be considered. The necessary bandwidth of the data collection system is somewhat definable in the LF noise study for which this antenna was built. The front-end filters of the receiver used in this noise study must be examined to see whether they provide the bandwidth necessary to properly characterize the impact of electrical storm activity on the GWEN receiver. The HP 8568B spectrum analyzer, the planned noise receiver, has fairly gently sloped bandpass filters. Because of this, a 10 kHz bandpass is used to isolate other signal sources, mainly in the broadcast band, which are present near the GWEN band. If a new receiver is found or built with a sharper sloping bandpass filter, the bandwidth of the recorded signal will be able to be expanded to 25 kHz--the total GWEN band. The first IF bandpass filter in the receiver used by the GWEN system is on the order of 3 kHz. The 10 kHz bandwidth proposed for the receiver in this noise study will thus assure enough detail in the noise data to analyze the effect of noise on GWEN reception. The rise time of the amplifying system, as well as its "ring" when exposed to strong impulsive signals, is of more concern in light of the nature of this study. A good experimental method to test for the rise time and the potential ringing in the amplifying systems is to subject the amplifiers to a square-wave signal, and observe the output of the antenna for distortion of the signal.

2.2 ANTENNA CONSTRUCTION

LF preamplifiers with gains of 40 dB are relatively easy to build. More complicated amplifiers, requiring more sophisticated components and more prudent design, are needed when the rise time of the active components becomes comparable to the period of the highest frequency needed.

A preamplifier circuit that can be built with easily obtainable components is presented in figure 2. Two such preamplifiers were built: one for each of the crossed-loops used in the omnidirectional antenna. These were bench tested, and their gain trimmed for equal performance. Trimming entails matching the 24-ohm resistors of the two amplifiers shown in the schematic until the gains of the two preamplifiers become equal.

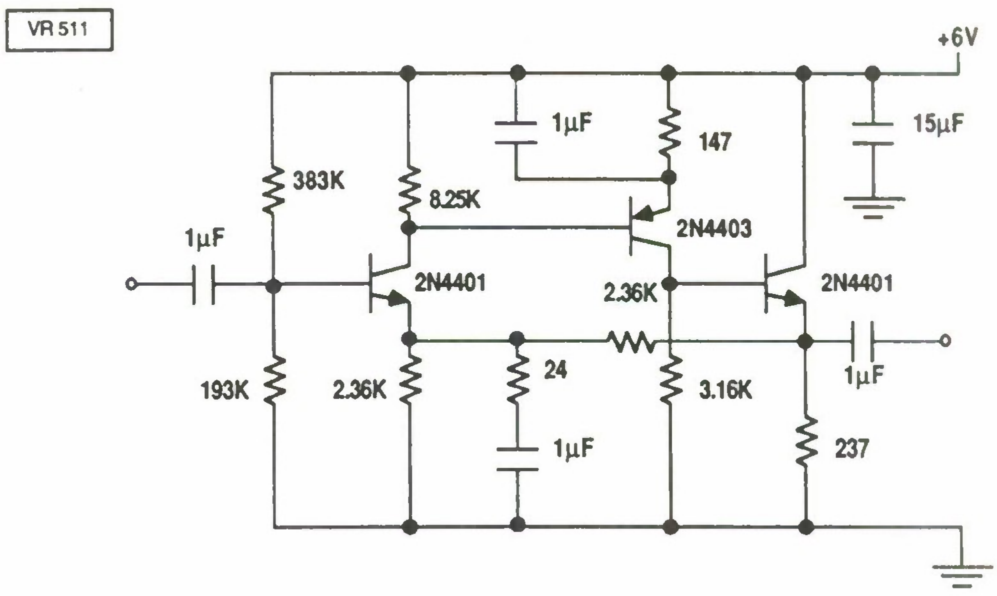

Figure 2. The Schematic of the 20-dB Preamplifier

Next, the phasing of the two loops was developed. To keep the gain of the respective loop signals equal, each amplified loop signal was phase-shifted by 45 degrees. A simple approach to phasing the loop signals, but one that was deemed sufficient for the 25 kHz bandwidth of interest, is to insert a series inductor in the circuit of one of the loops and a series capacitor in the other. Along with these phasing elements, series resistances equal to the magnitude of the impedance of the reactive components at 162.5 kHz are inserted on each leg of the antenna. This series resistance causes these phasing elements to have their 3-dB points at mid-GWEN band. Each signal then has equal real and imaginary parts at mid-band, and are thus 90 degrees out of phase. Because these phasors are also single-pole high- and low-pass filters, their roll-off is on the order of 6 dB/octave. The error in phasing and amplitude even on the edge of the GWEN band is expected to be small, since the frequency variation is less than one-tenth of a wavelength at the band edge, or about 28 degrees.

To combine the two signals evenly, an active combiner was designed and implemented. It was necessary to design and implement an active combiner whose feedback loop would provide a virtual ground where the two signals could be inserted. This was necessary to isolate the sensitive phasing elements from each other as well as from any series impedance differences before or after these elements. The combiner takes the form of a unity gain amplifier. The phasing elements are connected to the unity gain amplifier in the feedback loop. After combination, the signal is passed through a final impedance stabilizing stage that reduces the output impedance of the antenna to make it compatible with a 50-ohm coaxial cable. The schematic of the phasor, combiner and the cable matching circuits is presented in figure 3.

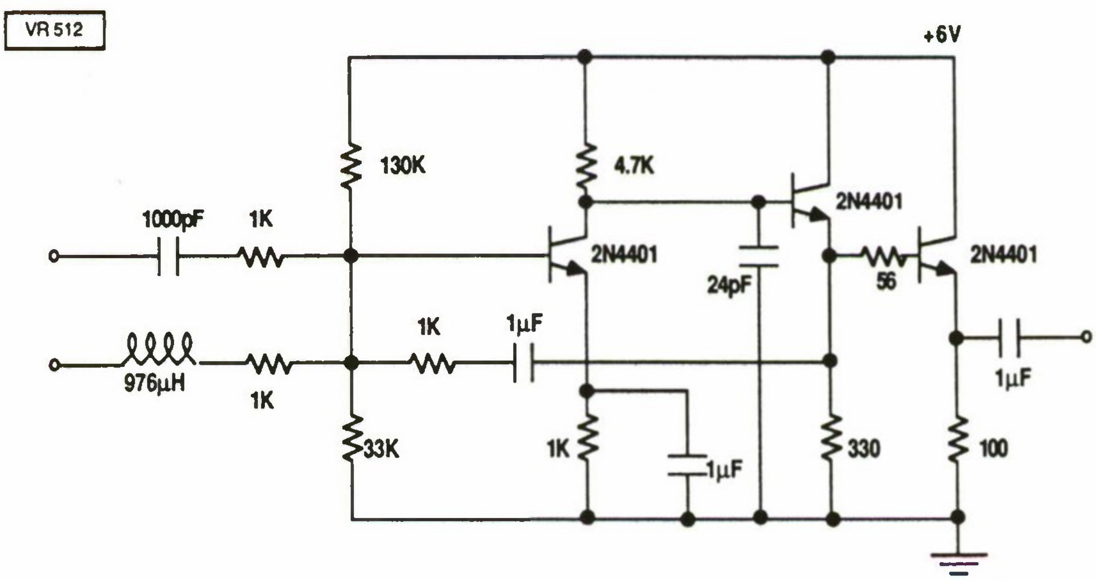

Figure 3. The Schematic of the Phasing and Combining Elements Used

Each loop of the crossed-loop antenna consists of four turns of wire, each turn having an area of 0.42 square meter. The effective height of these loops at mid-band (162.5 kHz) can be calculated [1] by

$$H_e = \frac{2\pi nA}{\lambda} \cos(\phi) \sin(\theta) \quad . \tag{6}$$

This yields an effective height of -44.8 dB relative to a meter (6 mm).

The form used to support these loops is PVC tubing having a diameter of 1.5 inches. Loop antennas are usually shielded from induced signals arising from ambient electric fields. Since the antenna frame used is made of non conducting PVC, coaxial cables with their sheaths notched at center-length were used as the receiving loops. The coaxial sheaths are grounded to common, and one end of the center conductor is shorted to ground. The signal induced in the loop from the magnetic field is carried to the preamplifiers on the center conductor of the other end of the coaxial cable.

The effectiveness of this type of wire shielding was tested by wrapping aluminum foil around the outside of the PVC tubing and grounding the foil to the common ground used in the amplifying system. The antenna was then set on the MITRE R-Building rooftop and the frequency spectrum of the incoming signal was recorded. This spectrum was compared to one taken when the antenna received signals without the aluminum foil shielding. Both spectra were found to be identical to each other, implying that the sheath of the coaxial cable effectively insulated the antenna loops from ambient electric fields.

The electronic components are housed in a cast metal box with four BNC bulkhead jacks for the four ends of the antenna coaxial cables used as receiving loops. An additional BNC bulkhead jack is provided on the box for the output signal of the antenna. Power is supplied to the antenna through a shielded twisted pair of wires at six volts dc. Figures 4a and 4b present pictures of the omnidirectional prototype.

2.3 POST-DESIGN TRIMMING AND ADJUSTMENTS

Oscillatory clipping was often encountered during bench tests of the crossed-loop antenna. After testing the coaxial receiving loops, it was found that the self-resonance of these loops was approximately 1.1 MHz. This frequency coincides with the frequency of the oscillatory clipping of the amplifiers. It was then realized that the self-resonance frequency of the loops is located in the AM broadcast band. Because of many locally strong broadcast carriers on or near the self-resonant frequency of the loops, it was suspected that the strong input signal of these broadcast stations was causing this oscillatory clipping.

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1. Johnson, R. C., and Jasik, H., Antenna Engineering Handbook, New York: McGraw-Hill, 1984.

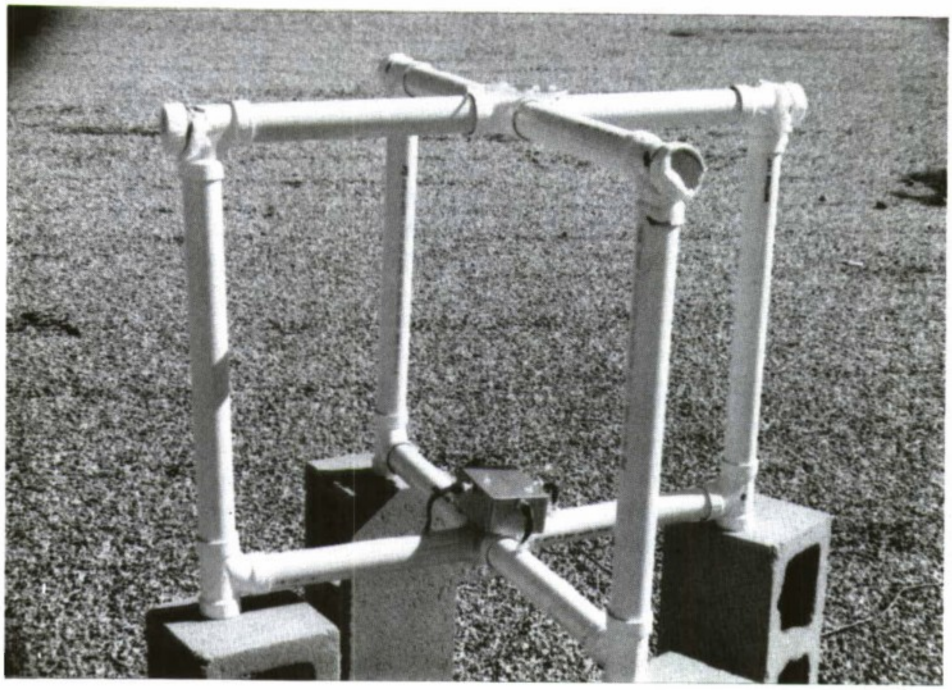

Figure 4a. The Crossed-Loop Antenna Frame

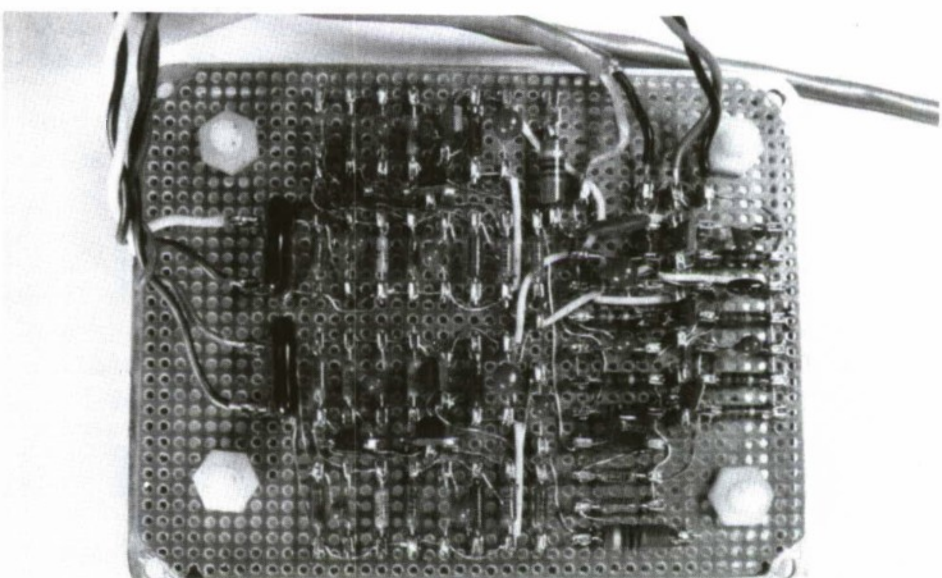

Figure 4b. The Active Component Housing

To help change the resonant frequency of the loops constructed, some shunt capacitance was added to the loops prior to amplification. To dampen the resonance of the loops in order to lower their Q, some shunt resistance was also added before amplification. The response of the loops with these shunt elements, before any electronic manipulation, is presented in figure 5 which shows a log-log graph of the normalized ratio of output to input voltage of the loop versus frequency.

After the fabrication of the loop frame and theoretical calculation of the effective height of the antenna before amplification, we determined that with a nominal signal amplification of 20 dB, enough sensitivity would be obtained to adequately receive the required 40 dB µV/m signal with the crossed-loop antenna. The reduction in preamplifier gain also helps in recording very strong signals, which are likely in an electrical storm noise study. The gains of the amplifiers were adjusted to approximately 20 dB by replacing the 24-ohm trim resistors with 198-ohm resistors.

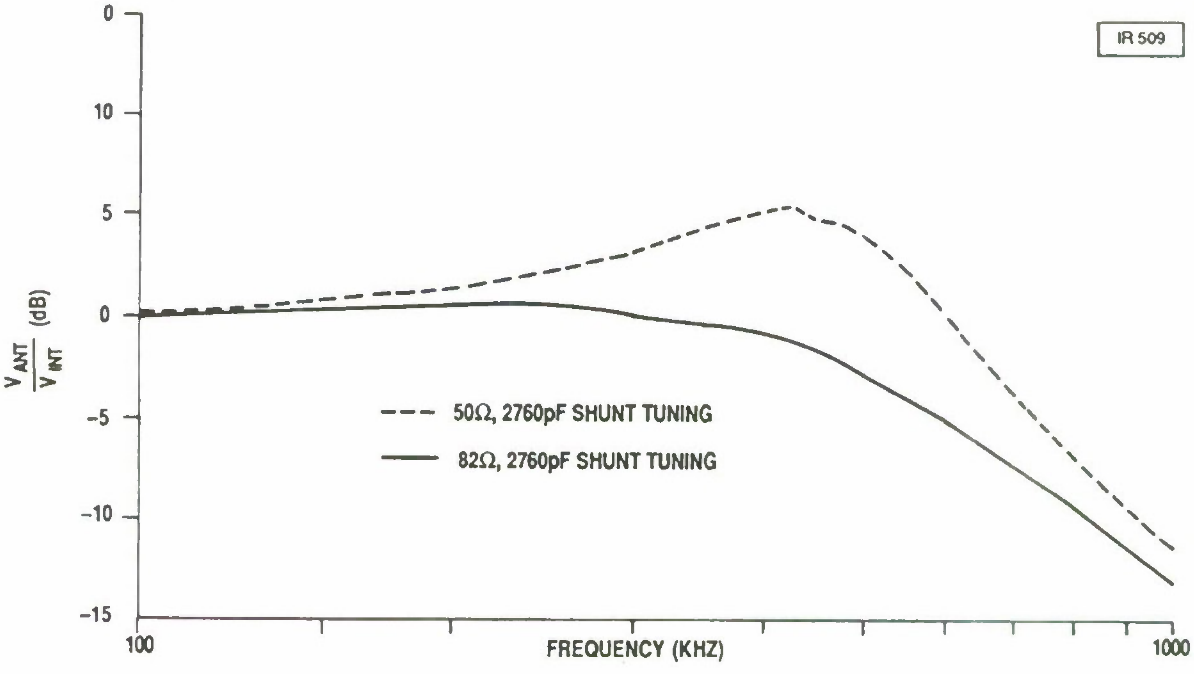

Figure 5. Normalized Voltage Produced on the Loop as a Function of Frequency

SECTION 3

ANTENNA CALIBRATION AND CHARACTERIZATION

3.1 THE OMNIDIRECTIONALITY TEST

The omnidirectionality of the crossed-loop antenna was tested to simplify the subsequent effective height measurements. An electromagnetic field source consisting of a loop frame wound with 30 windings of coated wire was used to calibrate and characterize the crossed-loop antenna. This transmission loop was tuned to GWEN mid-band (162.5 kHz) with series capacitance, and excited with a sinusoidal signal passed through a 1-watt amplifier.

To test the omnidirectionality of the crossed-loops, the magnitude of the antenna output was measured with the antenna turned azimuthally and the source loop kept stationary. The output signal of the antenna was measured with the HP 8685B spectrum analyzer and the signal recorded when the antenna was oriented in four quadrilateral directions. These measurements are presented in table 1 for five frequency samples in the GWEN band. The response of the receiving loop varies at different frequencies because of the tuning of the transmit antenna. Therefore, the data of table 1 was tabulated as the power input the spectrum analyzer, without converting the data to field strength. The ellipticity of the receive antenna response to the source, relative to a defined north-south leg of the antenna, is also presented in table 1. The maximum deviation is, as anticipated, negligible compared to the possible error in the effective height calculations.

Table 1. Omnidirectionality Data (in dBm)

	Frequency (kHz)				
	150	156.25	162.5	168.75	175
Direction					
North	-44.6	-38.3	-31.8	-44.2	-51.6
East	-43.0	-37.1	-32.0	-43.9	-51.5
South	-45.9	-39.2	-31.8	-43.8	-50.7
West	-44.4	-37.7	-32.0	-44.8	-52.4
Maximum Deviation (dB)	2.9	2.1	0.2	1.0	1.7

3.2 CALIBRATION

Since the antenna was nearly omnidirectional, a single value representing its effective height could be determined. The calibration began by inserting a 2-inch loop antenna, matched to a 50-ohm line, in the controlled fields of a Crawford cell. The Crawford cell is essentially an expansion of a coaxial cable used in the Transverse Electromagnetic Mode (TEM). The internal fields can be determined either by direct measurement or by a calculation from a known applied voltage. If terminated in 50-ohms, the characteristic impedance of the Crawford cell will be flat over its usable frequency range (near dc to 400 MHz). The possible error in field strength within the Crawford cell is a maximum of 2 dB from National Bureau of Standards (NBS) standards [2].

Once the effective height of the 2-inch loop was measured through the frequency range of interest, the effective height of a larger, more sensitive loop, could be obtained. The 2-inch loop was placed coplanar (and coaxial) to the Electro-Metrics ALR-25M 16-inch loop and field intensity readings of a synthesized electromagnetic field were taken from both loops on the HP 8568B spectrum analyzer. The effective height of the 16-inch Electro-Metrics loop was measured with the assumption that both loops experience the same magnetic field. This measured effective height is within 2 dB of the antenna height originally published by the manufacturers.

The same technique was employed to obtain the effective height of the crossed-loop antenna. Having previously verified the omnidirectionality of the crossed-looped antenna, its orientation to the incoming electromagnetic signal was not carefully chosen, but was kept constant during the measurement.

The electromagnetic field source and the 16-inch and crossed-loop antennas were moved to the far end of the MITRE R-Building parking lot, which offers a wide-open space relatively free of massive scattering objects. The calibrating procedure described above was repeated, and the measured effective height of the active LF crossed-loop antenna in the frequency range of interest is presented in table 2.

The data in table 2 is plotted and presented in figure 6. Since all quantities are in decibel levels, the calibration factor is the expressed effective height in dB relative to one meter. With this data a least-square fit was applied. This shows the antenna as having a calibration factor of minus 28.2 dB relative to a meter at GWEN midband.

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2. Crawford, M. L., "Generation of Standard EM Fields Using TEM Transmission Cells," IEEE Transactions on Electromagnetic Compatibility, Vol. EMC-16, No. 4, Nov 1974.

Table 2. The Effective Height of the LF Crossed-Loop Antenna

Frequency (kHz)	Effective Height (dB relative to 1 meter)
150	-28.9
151	-28.2
152	-28.0
153	-27.5
154	-27.3
155	-27.8
156	-28.0
157	-28.5
158	-27.8
159	-28.1
160	-28.6
161	-28.1
162	-28.1
163	-27.8
164	-28.1
165	-28.4
166	-28.0
167	-26.9
168	-26.9
169	-28.6
170	-28.7
171	-29.3
172	-28.6
173	-28.5
174	-28.9
175	-28.8

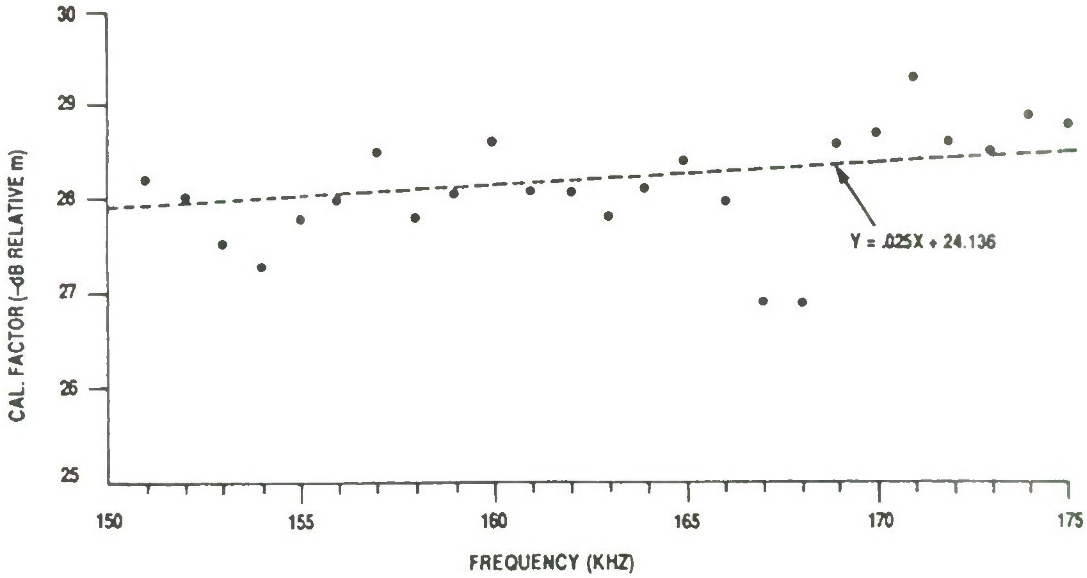

Figure 6. The Calibration Factor as a Function of Frequency

3.3 DYNAMIC RANGE CALCULATIONS

As previously discussed, the maximum field strength which the antenna will detect before saturating is of paramount importance. The receiving system will not detect all impulsive noise since lightning activity, when close enough to the antenna, can produce field strengths of many kilovolts per meter. The dynamic range needed by the antenna is then controlled somewhat by the dynamic range of the receiver and recording equipment. An ample dynamic range margin above the expected GWEN signal level is all that can be expected from the antenna for this noise study.

It was determined from laboratory measurements that saturation of the active elements of the antenna occurs at an input voltage of 0.355 V peak-to-peak (p-p) for one set of loops and 0.368 V(p-p) for the other set. Analyzing the lesser voltage, 0.355 V(p-p) can be rewritten as 111 dB μV peak voltage. The open circuit effective height of the antenna loops without the amplification was calculated to be -44.8 dB relative to a meter. Subtracting the effective height from the maximum voltage gives a maximum root-mean-square (rms) field strength of 146.8 dB μV/m before saturation.

The largest impulsive signal amplitude recently recorded in the noise study associated with GWEN has been 97 dB μV/m taken with a 1-kHz bandwidth receiver. The bandwidth of the antenna amplifiers can be taken from dc to the knee of the low-pass filter (500 kHz) created by the shunt capacitance applied to the loops. If it is assumed that the atmospheric noise is approximately the same magnitude in the frequency band which passes the low-pass filter, the amount of power entering the antenna amplifier can be represented by an increase of 54 dB peak voltage in the 10-kHz bandwidth recorded signal. This "broadband adjustment" can be applied to the rms voltage of the largest spike yet recorded, and puts the spike amplitude at 142 dB μV/m (rms). The LF crossed-loop antenna, therefore, provides a 4.8 dB margin over the largest impulsive signal yet recorded before clipping.

Since the electrical storm that caused the 97-dB μV/m noise spike was not visible or audible in the vicinity of the MITRE R-Building recording system, it is apparent that the amplitude of signals emanating from electric storms in close proximity of the receiving system could easily saturate the elements of the active crossed-loop antenna. Yet, from the figures measured and calculated, the crossed-loop antenna in its present design has 103 dB margin over the minimum required sensitivity of the incoming signal. This margin gets crossed so infrequently that it has been judged acceptable by all investigators taking part in this study.

3.4 RISE TIME MEASUREMENTS

A final necessary measurement is that of the rise time of the electronic amplifiers. The transistors involved in the amplifiers must have a fast enough rise time to amplify the incoming signal without appreciable distortion. Figure 7 is an oscilloscope display of a square-wave signal, as well as the amplifier's response to the square-wave input. The square wave signal was fed into the antenna system without the shunt capacitive/resistive elements inserted to tune the antenna loops. The amplifiers are shown to have a rise time of approximately 125 nanoseconds, which corresponds to a period of 8 MHz. From this data it can be deduced that no appreciable distortion of LF signal amplitude will be due to the amplification components of this antenna.

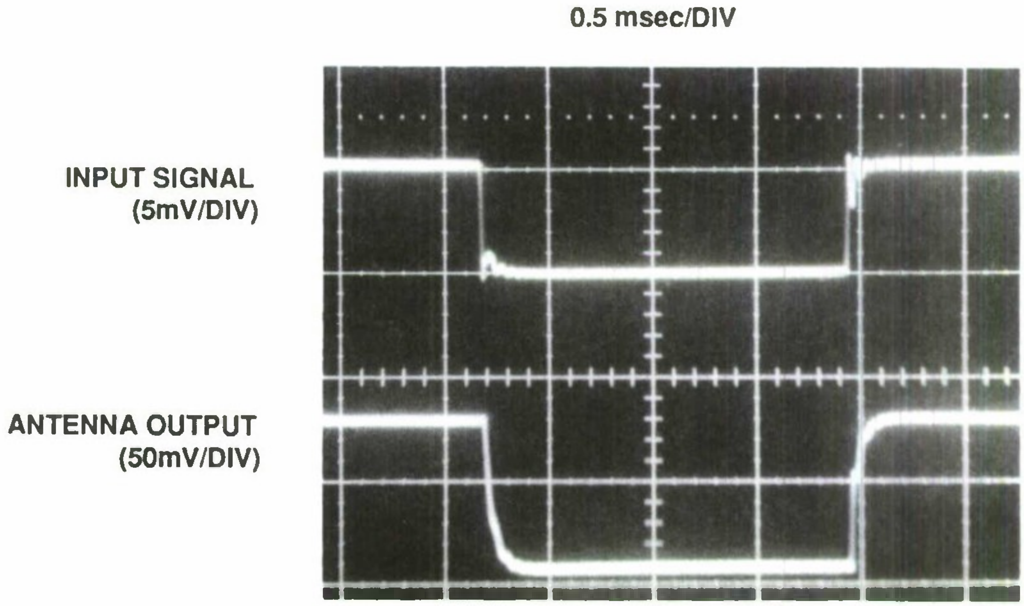

Figure 7. The Input Signal and Response of the Active Components of the Amplifier

SECTION 4

CONCLUSION

A crossed-loop antenna that is essentially omnidirectional over the GWEN band has been successfully built. This antenna is calibrated, through its effective height, to within 2 dB of the NBS standard. It has a dynamic range of approximately 200 dB. The antenna is substantially more sensitive than a GWEN antenna, judging from a comparison of their effective heights. This antenna is portable in the sense that its effective height does not depend greatly on ground plane placement. Even though some reactive elements, chosen to resonate at GWEN midband, are included in the combining circuits of the antenna, the effective height of the antenna does not change greatly over the GWEN band.

The antenna described above will be used in atmospheric noise measurements and will allow a quantitative characterization of atmospheric noise in the GWEN band. The antenna will also be used in calibrated field-intensity measurements of GWEN signal packets. The omnidirectional character of the antenna will allow the measurement of transient signals such as GWEN packets to be made, since no orientation of the antenna towards a signal maxima is necessary. In the past, this required orientation procedure has always been an obstacle in GWEN packet measurement.

As seen from the rise time measurements of section 3.4, the antenna can be used to measure narrow-band signals having frequencies of up to about 2 MHz without any appreciable distortion. The only design changes necessary would be to adjust the phasing components so that their 3 dB points are at the frequency of interest. Further changes may be needed to the shunt capacitors used as low-pass filters against the broadcast band.